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DEVELOPMENT OF TEST METHODS FOR MEASURING DAMPING OF FIBER-REINFORCED MATERIALS

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June 1970

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U.S. ARMY MATERIEL COMMAND

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DEVELOPMENT OF TEST METHODS FOR MEASURING DAMPING OF FIBER-REINFORCED MATERIALS

Final Report

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ABSTRACT

The objective of this work was to develop a test method, or methods, for the measurement of damping of fiber-reinforced plastics. Damping is a measure of the energy loss of a material subjected to cyclic strain. This parameter has a major effect on the mechanical behavior of dynamically loaded structures. A number of test methods were reviewed for applicability to testing fiber-reinforced plastics. Two methods were selected: free-free vibration and forced vibration, both using a thin beam in transverse vibration. The free-free method gives better accuracy, and the forced vibration method allows measurement of damping at various stress levels. The accuracy of each method was evaluated by measuring the damping of 2024-T4 aluminum, for which theoretical and experimental values are well established.

LIST OF SYMBOLS

c	specific heat per unit volume, psi
E	modulus of elasticity, psi
f_1	frequency below resonance frequency at which amplitude is 3 db less than that at resonance, Hz
f_2	frequency above resonance frequency at which amplitude is 3 db less than that at resonance, Hz
f_n	frequency at resonance, Hz
g	damping or tangent of the angle between strain and stress
h	thickness of cantilever beam, ft
k	thermal conductivity, lb/sec ^{o}F
T	absolute temperature, ^{o}K
W	energy, ft-lb
ΔW	change in energy, ft-lb
α	coefficient of linear expansion, in./in./^{o}F
ω	vibration frequency, rad
τ	characteristic relaxation time, ft^4/sec ^{o}F

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INTRODUCTION

As a result of the outstanding strength-to-weight ratio of many fiber-reinforced plastics (FRP), a variety of applications of these materials are being considered for future aircraft structural components. In the majority of these applications, dynamic structural behavior is a primary consideration.

The viscoelastic properties of materials become important for dynamic loading. One of these properties, damping, is of particular interest to the aircraft designer for the following reasons: damping limits the amplitude of vibration in a structure that is being excited at its natural frequency, damping may be a significant factor in noise reduction, and it may be a source of dynamic instability in rotating shafts.

Our knowledge of the physical properties of FRP materials is largely composed of static test data. Information on damping properties of these materials is practically nonexistent. For these reasons, measurement of damping in FRP was made the primary objective of this effort.

DEFINITION OF DAMPING

The conversion of elastic energy to heat is termed internal friction or damping. Mathematical representation of this phenomenon varies considerably in the literature, being largely determined by the set of physical parameters chosen for measurement. Ye. S. Sorokin[1] describes nine groups of methods for measuring damping, each of which produces a quantitative measure of internal friction and has a different mathematical representation.

The definitions used throughout this report are based on a linear relationship between stress and strain, and on the dissipative forces being proportional to the velocity. Damping is defined as the tangent of the angle by which the strain lags stress. For free-free conditions, the tangent angle may be obtained by calculating the logarithmic decrement (log dec), which is the natural logarithm of the ratio of any two successive measured amplitudes of vibration, and by using the following relationship:

$$g = \frac{\text{log dec}}{\pi}$$

For forced vibration of a material, the damping may be calculated by taking the ratio of the difference in frequency between the 3-db levels on either side of the resonance peak to the resonance frequency.

$$g = \frac{f_1 - f_2}{f_n}$$

Derivations for the above relations are contained in Reference 2.

TEST METHODS

A variety of test methods were considered for measuring the damping of fiber-reinforced plastics. The more significant of these are described below.

ULTRASONIC METHODS

Most such methods call for the injection of a sonic signal into the material and the measurement of the attenuation of this signal across a known path length in the material. The configuration that gives the best results is a long, thin rod, which is not an amenable shape for composites with cross-ply layups.

THERMAL METHODS

These methods usually rely on temperature change due to heat generated by damping and on thermodynamic relationships for change in temperature and change in energy, ΔW. The total energy, W, is calculated from stress deformation, and the damping is the ratio $\Delta W/W$. Thermal methods are limited in accuracy by a number of factors, the more important of which is that when the material has a low value of damping, high stresses are required in order to obtain a measurable temperature change.

FREE DECAY OF VIBRATIONS

This is one of the better-known methods for measuring damping. In principle, the damping is proportional to the ratio of successive amplitudes of vibration of the specimen. High accuracy of measurement can be obtained because very little energy is lost to the supports holding the specimen if the experiment is carefully done. Because of the inherent accuracy of this method, it was selected for further development.

HYSTERESIS MEASUREMENTS

If the stress/strain relationship is plotted for a material undergoing cyclic strain, the damping can be calculated from the resulting hysteresis loop.

For materials with large damping, this method can be quite accurate and convenient; however, for small values of damping, difficulties in measuring the strain cause inaccuracies.

FORCED OSCILLATIONS IN THE VICINITY OF RESONANCE

If the amplitude of vibration versus the frequency of vibration of a material is recorded, then the damping may be calculated from this curve. Although this method is not highly accurate, primarily owing to loss of energy to the supports, it is useful since one may measure damping at high stress levels; for this reason, this method was also selected for development.

EXPERIMENTAL PROCEDURES AND APPARATUS

FREE-FREE METHOD

The first method developed was the free-free vibration of a thin beam. In this apparatus, shown in Figure 1, the beam is suspended at the nodal points for the first mode of vibration by No. 50 cotton thread attached to the adjustable supports. These supports rest on a rigid bed to allow insertion and removal of the assembly from the vacuum chamber. The thread suspension serves to decouple the beam vibrations from the support fixture. Unless decoupling is used, a significant transfer of energy from the beam to the supports may occur.

The beam is excited by an electrodynamic relay with a core translation of 0.6 inch when energized. A helical spring retracts the core of the coil when the coil is deenergized.

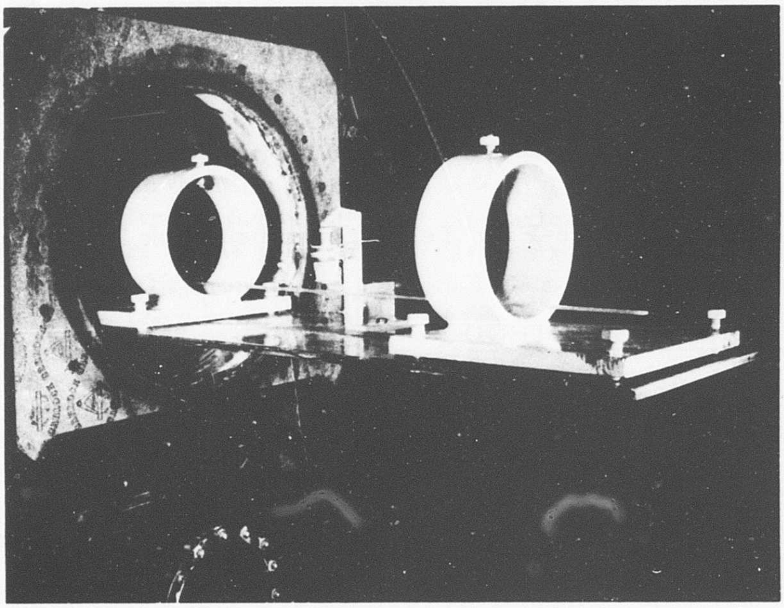

Figure 1. Free-Free Test Apparatus.

The vibration amplitude of one end of the beam is measured with a non-contacting optical-electronic device (Optron). Signals from this instrument are put through a ±2.5-Hz band-pass filter centered on the vibration frequency of the beam; then they are passed on to a recording light beam galvanometer. A block diagram of this circuit is shown in Figure 2. The filter is needed because the optical electronic measuring device has appreciable noise when measuring small deflections. The attenuation of the signal by this filter does not affect the measurement of damping, as this parameter is proportional to the ratio of successive measurements. Provided that the attenuation is constant throughout the amplitude range of the signal, the effect of this attenuation cancels out.

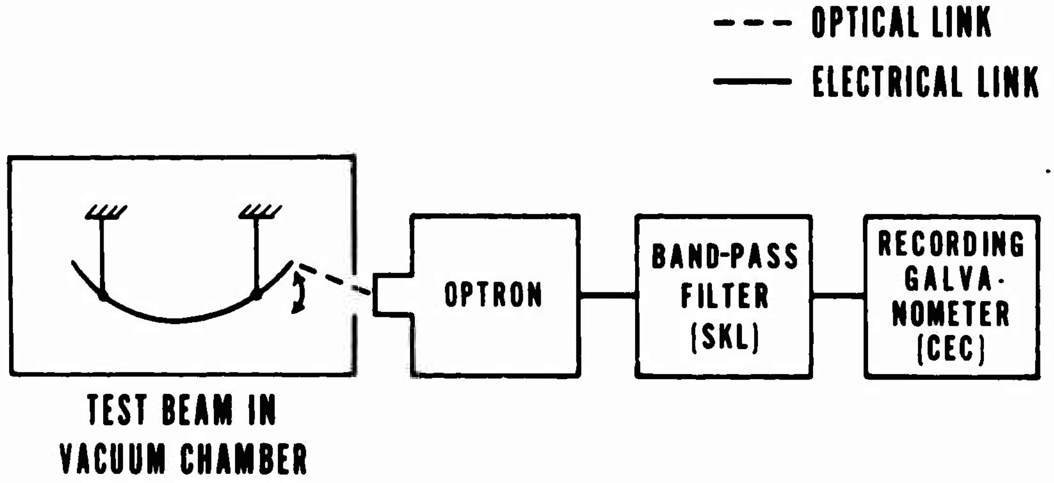

Figure 2. Free-Free Test Apparatus Block Diagram.

FORCED VIBRATION METHOD

This method is a modification of the method used by Granick and Stern[3] for damping measurements on aluminum. The basic modification made to their test method was in the geometry of the specimen. Granick and Stern used a double cantilever machined beam with a raised center section to allow mounting of the beam to a vibrator. This beam geometry is unsuitable for fiber-reinforced plastics because of obvious fabrication difficulties. If a flat laminate were machined with a raised portion in the center, discontinuous fibers on the beam surface would result, primarily in the root area. The effects of such discontinuities are unknown, and considerable difficulty is encountered in producing identical specimens.

A number of gripping techniques were tried for converting a flat beam into a double cantilever beam. The best suited of these was the use of an epoxy shoulder molded to the beam on each side, as shown in Figure 3.

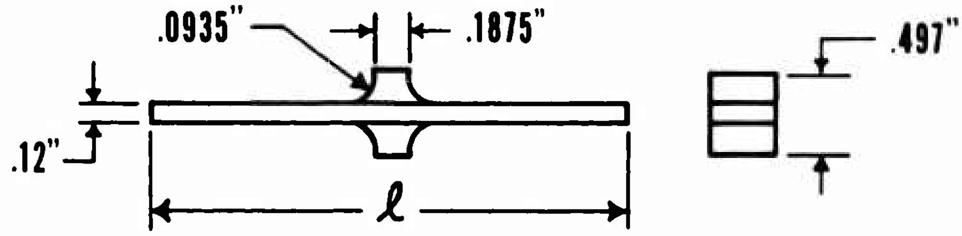

Figure 3. Forced Vibration, FRP Test Specimen Geometry.

The double cantilever beam was mounted on the vibrator head of an electrodynamic shaker system (see Figure 4), and the beam-vibrator head assembly was placed in a vacuum chamber subject to 0.2mm Hg. The beam was excited by driving the shaker table at a resonant frequency of the test specimen. The vibration amplitudes of both ends of the beam were measured with Optrons. Signals from these instruments were processed in a manner similar to the free-free apparatus except that the output of the Optron was fed directly to a logarithmic converter and then to a servo X-XY plotter (tip amplitude of each cantilever versus frequency) as indicated on the block diagram, Figure 5. Root stresses in the double cantilever beam were evaluated by measuring the dynamic tip deflection and computing the stresses from the equations of dynamic displacement. The driving force was sinusoidal and was adjusted to give the desired root stress (by measuring tip deflection) at the resonant frequency of the beam. The frequency was then reduced to a value at which the amplitude of vibration of the tip was 3 db down from the amplitude at resonance. The frequency was then increased in discrete increments of (typically) .01 Hz to the 3-db level on the other side of resonance. The change in frequency necessary to accomplish this and the resonant frequency were recorded. It should be noted that this method differs from that of Granick and Stern in that they essentially measure the "Q" of the beam at resonance to obtain damping. This is an acceptable method; however, the equation used by Granick and Stern from Reference 4 is correct only for tests run in a vacuum. If air drag is present, the equation gives values of damping (material and air) which are higher than the true value. Values of damping given in Reference 3 for aluminum beams tested in air are therefore questionable.

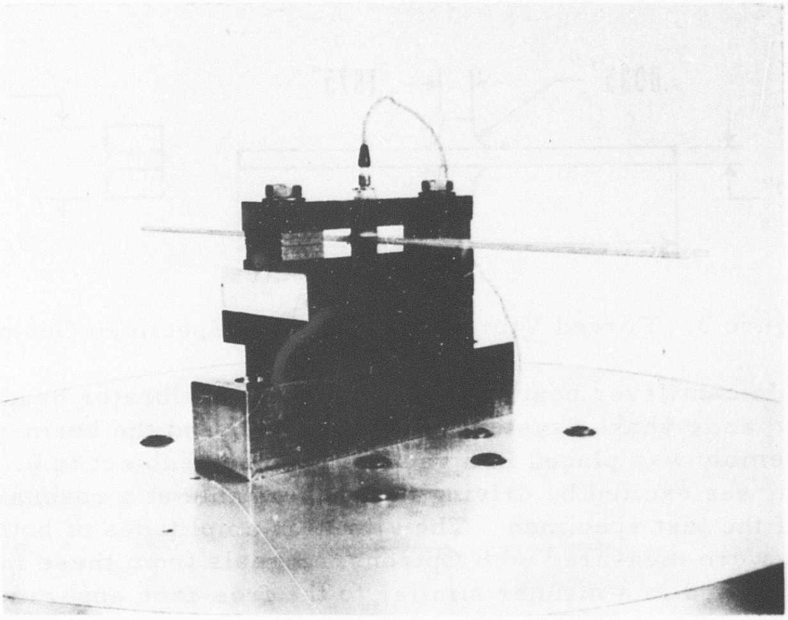

Figure 4. Double Cantilever FRP Beam Mounted on Electrodynamic Shaker Head.

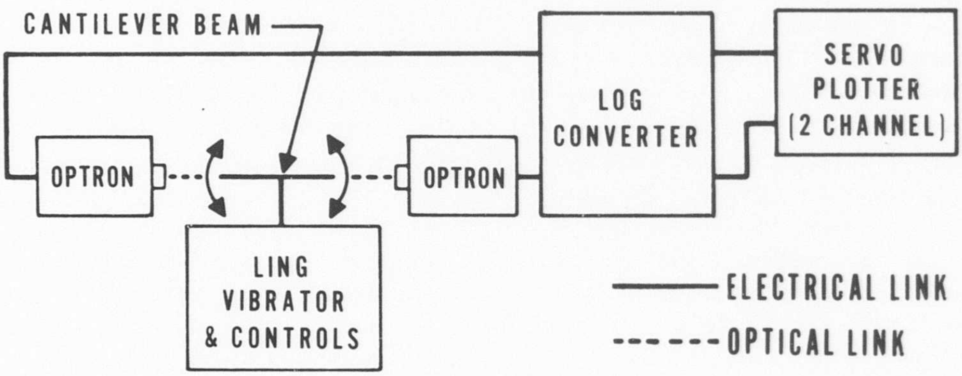

Figure 5. Forced Vibration Test Apparatus Block Diagram.

EXPERIMENTAL RESULTS

ALUMINUM

To obtain a figure of merit for the two systems of measuring damping, 2024-T4 aluminum was measured in each apparatus. The damping of 2024-T4 aluminum has been established experimentally[3] and theoretically[5] by Zener's anelastic theory for metals and is therefore well suited for this purpose.

A thin metal beam in transverse vibration has damping according to Zener as follows:

$$g = \frac{\alpha^2 ET}{c} \left[\frac{\omega\tau}{1 + \omega^2 \tau^2}\right]$$

where α = coefficient of linear expansion, in./in./$^{\circ}$F

c = specific heat per unit volume, psi

E = modulus of elasticity, psi

T = absolute temperature, $^{\circ}$K

ω = vibration frequency, rad

g = material damping coefficient

τ = characteristic relaxation time, $\frac{h^2 c}{\pi^2 k}$

h = thickness of cantilever beam, ft

k = thermal conductivity, lb/sec $^{\circ}$F

Examination of this equation shows that for a given test specimen, ω is the only variable, and g goes through one maximum as ω is varied. Values for the physical constants appearing in the equations were extracted from Reference 6, except for the modulus of elasticity, the specific heat, and the thermal conductivity, which were measured on representative samples of the same material used for damping studies.

An experiment was conducted so that the natural resonance of the test beams varied from below to above the frequency at which the maximum damping occurs. In Figure 6 this peak frequency is plotted versus beam thickness. The natural resonance of the beam versus the beam thickness and length has also been plotted on Figure 6. As shown on the plot, a length corresponding to a thickness between .065 inch and .07 inch gives a reasonable length beam for testing. Shorter beams have too small an aspect ratio for their motion to be approximated by the linear beam equation, and longer beams develop too great a sag for realistic testing.

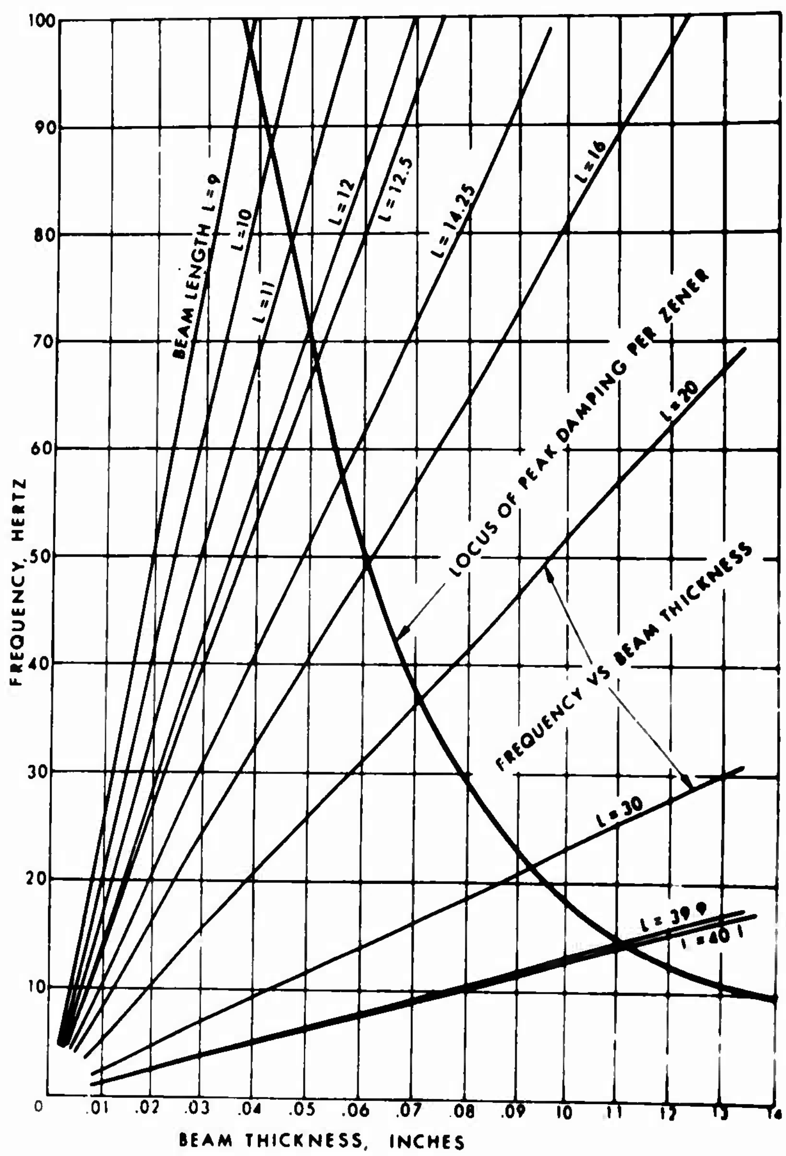

Figure 6. Plot of Free-Free Beam Vibration Frequency Versus Beam Thickness for Different Beam Lengths, Showing Locus of Peak Damping per Zener.

Experimental values obtained on a sample of 2024-T4 aluminum using the free-free apparatus are compared with calculated values from Zener's equation in Figure 7. The close agreement of these results demonstrates that the free-free apparatus gives the material damping quite accurately.

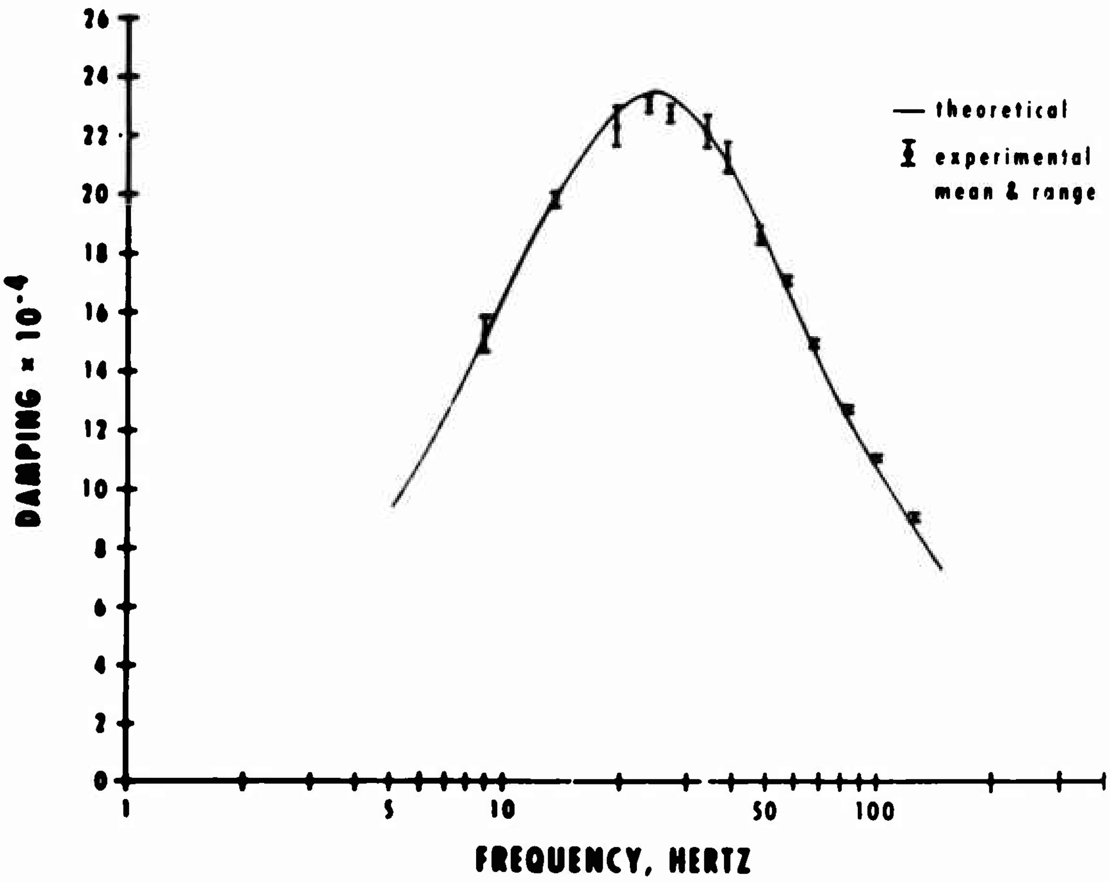

Figure 7. Damping Versus Frequency for 2024-T4 Aluminum; Theoretical and Experimental.

FIBERGLASS

Fiber-reinforced plastic beam specimens were cut from panels laminated with type 1009-26S preimpregnated, nonwoven fiberglass tape, which was cured between heated platens under 30-psi pressure at 325°F for 27 minutes. Fiber orientations were 0° (unidirectional) for one type of specimen, and 0° plies alternated with 90° plies (0° on both face plies) for the other type of specimen.

Physical dimensions were chosen to give similar frequency values for beam dimensions comparable to the aluminum beams tested. Tests were conducted using both the free-free and the forced vibration method.

Test results for both methods are given in Tables I and II and are graphically depicted in Figure 8. One can observe a difference between the damping values obtained by the free-free method and those resulting from the forced vibration method. While there is a difference in level of stress at which the results were generated, it is believed that this was not the major cause of the difference in damping values observed; the trend indicated by the curves in Figure 8 is that damping values for FRP at a given frequency will remain constant for those stress levels at which the proportional limit is not exceeded. Rather, it is believed that the difference in damping measured between the two techniques is due mostly to the difference in boundary conditions (the forced vibration technique can lose more energy at the specimen support).

TABLE I. DAMPING VALUES OF FRP, UNIDIRECTIONAL LAYUP, AS MEASURED BY THE FREE-FREE METHOD

Pressure (mm Hg)	Temperature (^{o}F)	Frequency (Hz)	Damping (x 10^{-4})
.09	80	15.29	10.71
.09	80	15.31	10.74
.10	79	20.00	10.22
.10	79	20.00	10.32
.10	80	24.79	9.91
.10	80	24.87	10.33
.10	78	28.35	9.84
.10	78	28.35	9.94
.10	77	30.00	9.92
.10	77	30.00	9.93
.10	78	40.00	9.75
.10	78	40.00	10.51
.09	72	50.00	11.05
.09	72	50.00	11.12
.09	73	70.00	9.67
.09	73	70.00	10.08
.09	73	90.00	10.91
.09	73	90.00	10.84
.09	73	110.00	13.45
.09	73	110.00	12.20
.09	73	110.00	12.79
.09	74	145.00	9.99
.09	74	145.00	9.89
.09	74	157.00	9.59
.10	74	157.00	10.12

TABLE II. DAMPING VALUES OF FRP, 0° - 90° LAYUP, AS MEASURED BY THE FREE-FREE METHOD

Pressure (mm Hg)	Temperature (°F)	Frequency (Hz)	Damping ($\times 10^{-4}$)
.20	76	17.70	23.91
.20	76	17.70	23.95
.20	75	28.63	26.00
.20	75	28.63	26.00
.20	72	50.35	24.20
.20	72	50.35	24.73
.30	73	90.00	25.97
.30	73	90.00	26.63
.20	75	158.00	26.20
.20	75	158.00	26.53

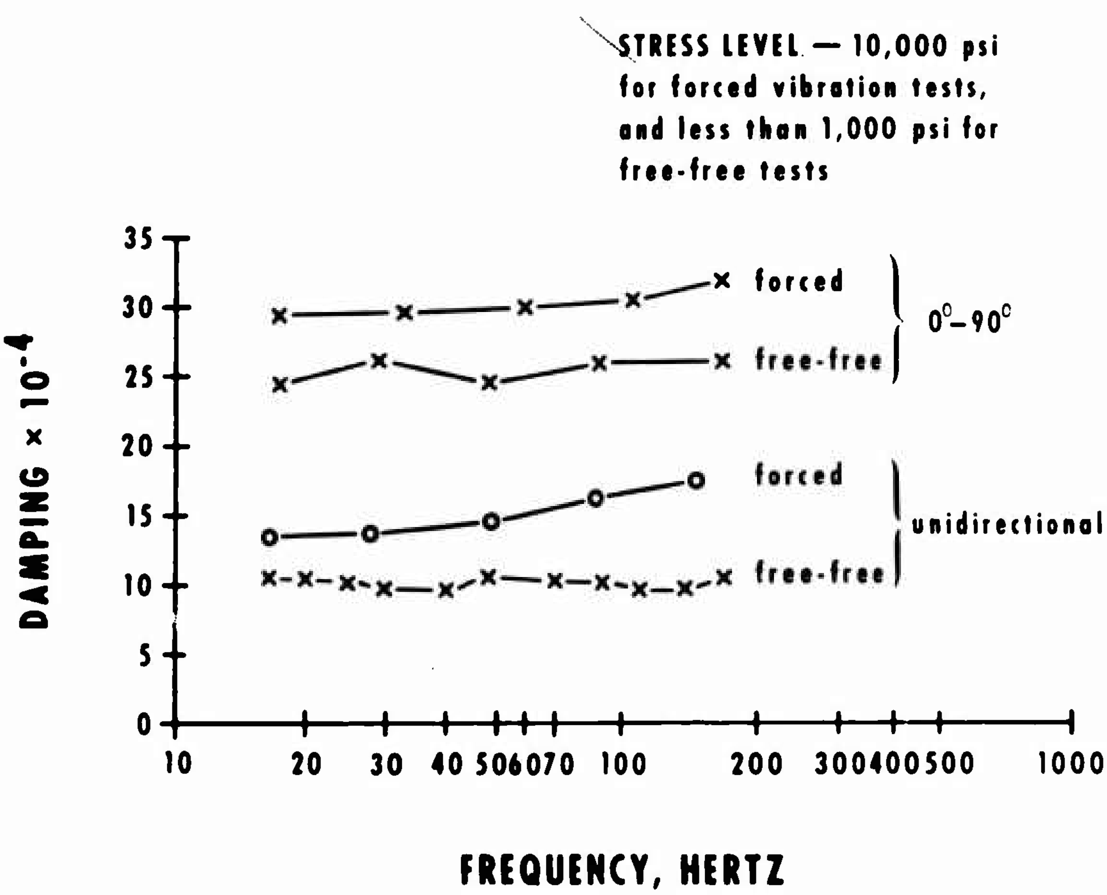

Figure 8. Damping Versus Frequency for Fiberglass, Unidirectional and 0° - 90° Layups; Forced Vibration and Free-Free Test Procedures.

CONCLUSIONS

It is concluded that:

1. Based on the close correlation between experimental and theoretical values of damping in 2024-T4 aluminum, the free-free test apparatus and experimental procedure described herein will yield true values of damping of thin beams in the frequency range of 16 to 157 Hz.

2. The forced vibration test method is suitable for measuring damping in fiberglass in the frequency range of 16 to 157 Hz and from 2000-psi root stress up to that value of stress at which the resonance curve becomes unsymmetrical.

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13. ABSTRACT

The objective of this work was to develop a test method, or methods, for the measurement of damping of fiber-reinforced plastics. Damping is a measure of the energy loss of a material subjected to cyclic strain. This parameter has a major effect on the mechanical behavior of dynamically loaded structures. A number of test methods were reviewed for applicability to testing fiber-reinforced plastics. Two methods were selected: free-free vibration and forced vibration, both using a thin beam in transverse vibration. The free-free method gives better accuracy, and the forced vibration method allows measurement of damping at various stress levels. The accuracy of each method was evaluated by measuring the damping of 2024-T4 aluminum, for which theoretical and experimental values are well established.

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